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Multi-Agent-Based Distributed State of Charge Balancing Control for Distributed Energy Storage Units in AC Microgrids

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Abstract— In this paper, a multiagent based distributed control algorithm has been proposed to achieve state of charge (SoC) balance of distributed energy storage (DES) units in an AC microgrid. The proposal uses frequency scheduling instead of adaptive droop gain. Each DES unit is taken as an agent and they schedule their own frequency reference given of the real power droop controller according to the SoC values of the other DES units. Further, to obtain the average SoC value of DES, dynamic average consensus algorithm is adapted by each agent. A small-signal model of the system is developed in order to verify the stability of the control system and control parameters design. Simulation results demonstrate the effectiveness of the control strategy and also show the robustness against communication topology changes.

Keywords—multiagent; distributed control; State-of-charge balance; distributed energy storage; AC microgrids; frequency scheduling; dynamic average consensus

I. INTRODUCTION

Microgrid is gaining more and more attention as one of the most potential technologies to increase efficiency and reliability of power systems. A microgrid can be defined as a small-scale distribution electrical grid consisted of distributed energy resources (DER) and dispersed loads, which can operate in both grid connected and island mode as an integrated controllable entity [1].

Due to the intermittent nature of renewable energy resource (RES) and the lack of inertia of power electronic converters, distributed energy storage (DES) units are essential to provide ancillary services to the grid and to balance electricity generation and consumption in islanded mode. Moreover, to increase the system reliability, more than one set of distributed energy system units tend to be needed [2].

Furthermore, SoC balance is often desirable among DES units, which present higher efficiency and State-of-Health (SoH) when their SoC is within a certain range which depends also on the technology, e.g. between 20% and 80%. If SoC of the all the DES units is consistent by making it balance, no single unit tends to go outside this range. Thus, the power capacity of the DES is maximized all the time, i.e., it is less likely that one of the units is forced offline due to very high or very low SoC, so that the instantaneous charging/discharging

power can be maximized. Several previous works have been done to achieve SoC balancing [2]-[10]. However, most of them are focused on DC microgrid systems, while little work has been done in this area for AC microgrids [4], [10]. For instance, in [10], a SoC-dependent adaptive droop function is proposed to balance DES units; however the system stability is very sensitive to the droop coefficient, so that large values may lead to system instability [11]. Moreover, centralized control can be used to manage DES [7], but they are prone to a single point of failure of the supervisory device. In this paper, a MAS based distributed control algorithm has been proposed to achieve state of charge (SoC) balance of distributed energy storage (DES) units in an AC microgrid. Taking each DES unit as an agent, frequency scheduling instead of adaptive droop gain is adopted to control its charging and discharging autonomously. The communication among the agents to obtain the global information necessary to make the local decision, i.e., the average SoC value of DES, is implemented through dynamic average consensus algorithm.

The rest of the paper is organized as follows. Section II briefly introduces the configuration of the example AC microgrid with MAS controlled DES. Section III describes the frequency scheduling method for balancing the DES units. Section IV presents multiagent based dynamic average consensus algorithm and complete control method of each agent is provided. In the last section, Hardware in the loop result is presented to show the effectiveness of the proposed control method. Finally, Section IV concludes the paper and possible future work.

II. SYSTEM CONFIGURATION

Fig. 1 shows an example of AC microgrid configuration, which consists of RES (wind and solar), AC load, and three DES units controlled by a multi-agent system (MAS). As the only grid forming component in the microgrid, DES is responsible to balance the mismatch between the power produced by RES and that needed by the load. Normally, the load is fed by RES when there is enough amount of power available, and DES is working in charging mode. When the output power from the RES is not enough and the microgrid is operating in islanded mode, DES switches to discharging mode. It is desired that during discharging mode, the DES unit with higher SoC will provide more power than the others, and

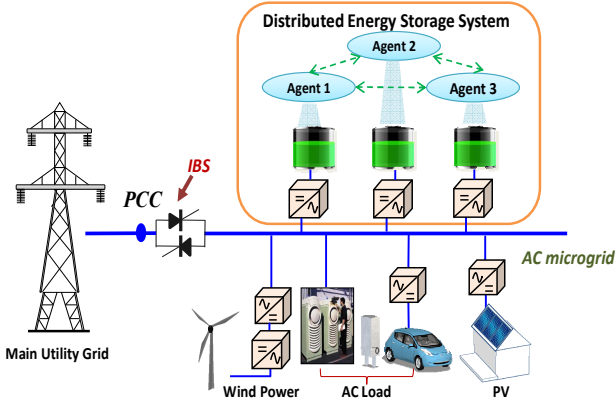


Fig. 1 AC microgrid with multiagent controlled DES

during the charging mode, the ones with lower SoC will absorb more power, so that the SoC balance among DES can be maintained.

III. FREQUENCY SCHEDULING FOR SOC BALANCING IN AN AC MICROGRID

A. Real power control based on droop

To make SoC of DES balance, real power of each unit should be regulated according to the SoC of the DES. Droop control is one of the most popular methods for real and reactive power regulation [12]. Not like reactive power, real power sharing is not sensitive to different line impedance and thus can be regulated well by the frequency droop controller as

$$\omega_i = \omega_{0i} - K_{p_i} P_i \quad (1)$$

There are two possibilities to change the way how real power shared, which is illustrated in Fig. 2. It can be seen that either changing the frequency droop gain Fig.2 (b) or changing frequency given can change the real power sharing. Previous work [4] and [10] has employed adaptive frequency droop gain to achieve SoC balance. Instead of adjusting the droop gain, the possibility of adaptive frequency given is investigated in the paper.

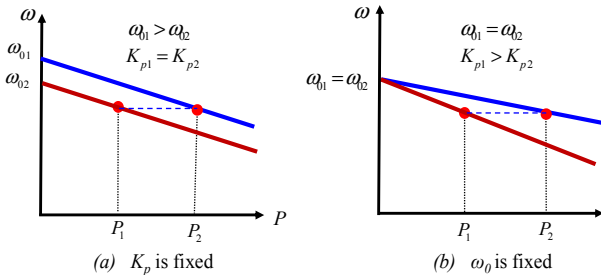


Fig. 2 Real power droop principle

B. Estimation of the SoC

Before introducing frequency scheduling for SoC balance, the SoC estimation method is described first. Although many techniques have been proposed to measure or monitor the SoC of a cell or the battery, charge counting or current integration is the most commonly used technique [3] and thus is chosen in this paper. The basic of simplified SoC calculation can be written as

$$SoC_i = SoC_i^* - \frac{1}{C_{e_i}} \int i_{b_i} dt \quad (2)$$

where i_{b_i} , SoC_i^* , and C_{e_i} are the output current, initial value of SoC, and battery capacity for unit i respectively.

If the power loss in the converter can be omitted and assume the output voltages of the batteries are the same, there exists following approximation for each DES unit.

$$P_i = P_{in_i} = V_{in} i_{b_i} \quad (3)$$

where V_{in} , P_i and P_{in_i} are the input voltage of the converter, output power of the converter, and input power of the converter, for unit i , respectively. Here we assume that values of the input voltage of all the converters are the same. So combining the (2) and (3), the SoC calculation can be written as

$$SoC_i = SoC_i^* - \mu \int p_i dt \quad (4)$$

$$\text{where } \mu = \frac{1}{C_{e_i} V_{in}},$$

C. Frequency scheduling for SoC Balance

In order to take SoC of all DES units into consideration, the frequency given ω_0 of real power droop in (1) is modified by adding an item respect to the values of SoC of all the units in the DES. The control diagram is shown in Fig.3, and the equation of the this method can be written as:

$$\omega_{0i} = \omega_{0i}^* + K_{SoC} (SoC_i - SoC_{mean}) \quad (5)$$

being SoC_{mean} the average value of SoCs of all DES units, K_{SoC} a proportional coefficient, and ω_{0i}^* the nominal individual frequency for agent i .

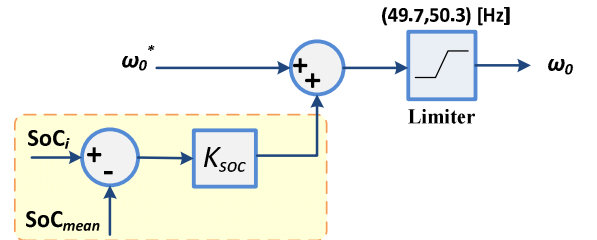


Fig. 3 Control diagram of frequency scheduling for SoC Balance

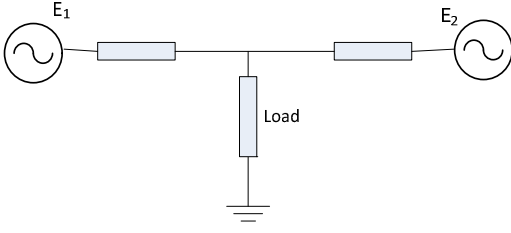


Fig.4 System topology for small signal analysis

D. Small signal model of frequency scheduling method for SoC Balance

In order to analyze the effects of the parameter K_{SoC} towards system stability, small signal model based on [13] is set up considering this newly added frequency scheduling controller. For simplicity, the model considers system with two DES units supplying a common load, and the topology is shown in Fig. 4.

In addition to (1), the characteristics of reactive droop is defined as

$$E_i = E_{0i} - K_{Q_i} Q_i \quad (6)$$

The local droop controller includes a low pass filter, expressed as

$$P_i = \frac{\omega_f}{\omega_f + s_i} p_i \quad (7)$$

$$Q_i = \frac{\omega_f}{\omega_f + s} q_i \quad (8)$$

where p_i , q_i and ω_f are measured real power and reactive power of DES unit i and cut-off frequency of the low pass filter, respectively.

According to (3), the controller of the frequency scheduling can be written as:

$$\omega_{01} = \omega_{01}^* + \frac{K_{SoC}}{2} (SoC_1 - SoC_2) \quad (9)$$

$$\omega_{02} = \omega_{02}^* + \frac{K_{SoC}}{2} (SoC_2 - SoC_1) \quad (10)$$

Considering (4), (9) and (10) can be small-signal perturbed as

$$\Delta\omega_{01} = \frac{\mu K_{SoC}}{2} \int (\Delta p_1 - \Delta p_2) \quad (11)$$

$$\Delta\omega_{02} = \frac{\mu K_{SoC}}{2} \int (\Delta p_2 - \Delta p_1) \quad (12)$$

Assuming that droop gains are the same for the two units, by perturbing (1), it yields

$$\Delta\omega_1 = \Delta\omega_{01} - K_p \frac{\omega_f}{\omega_f + s} \Delta p_1 \quad (13)$$

$$\Delta\omega_2 = \Delta\omega_{02} - K_p \frac{\omega_f}{\omega_f + s} \Delta p_2 \quad (14)$$

Taking a common d-q reference frame for all the converters, the vector \vec{E} can be represented as

$$\vec{E} = e_d + j e_q \quad (15)$$

The angle and magnitude of the vector can be written as

$$\delta = \arctan\left(\frac{e_q}{e_d}\right) \quad (16)$$

$$E = |\vec{E}| = \sqrt{e_d^2 + e_q^2} \quad (17)$$

Considering $\Delta\omega(s) = s\Delta\delta(s)$, and combining (11), (12), (13), (14), (6) and (8), the state equation for each converter can be obtained as

$$\begin{bmatrix} \Delta\dot{\omega}_i \\ \Delta\dot{\omega}_{di} \\ \Delta\dot{e}_{di} \\ \Delta\dot{e}_{qi} \end{bmatrix} = M_i \begin{bmatrix} \Delta\omega_i \\ \Delta\omega_{0i} \\ \Delta e_{di} \\ \Delta e_{qi} \end{bmatrix} + C_i \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} \quad (18)$$

where the detailed expressions for matrix M_i and C_i can be obtained from above mentioned equations.

Considering the expressions of active and reactive power supplied by each converter,

$$P_i = e_{di} i_{di} + e_{qi} i_{qi} \quad (19)$$

$$Q_i = e_{di} i_{qi} - e_{qi} i_{di} \quad (20)$$

Linearizing the equations above at the equilibrium point, we get the following expression in a symbolic form,

$$\Delta S = I_s \Delta e + E_s \Delta i \quad (21)$$

where I_s and E_s are constant matrices with respect to the state at equilibrium point, and $\Delta e = [\Delta e_{d1}, \Delta e_{q1}, \Delta e_{d2}, \Delta e_{q2}]^T$, $\Delta i = [\Delta i_{d1}, \Delta i_{q1}, \Delta i_{d2}, \Delta i_{q2}]^T$.

Perturbing the nodal admittance matrix equation of the network, we get

$$\Delta i = Y_s \Delta e \quad (22)$$

where Y_s is the nodal admittance matrix of the network.

Substituting (22) in (21), we can get

$$\Delta S = (I_s + E_s Y_s) \Delta e \quad (23)$$

The state equation of the whole system can now be obtained as

TABLE I. CONTROL PARAMETER FOR EACH DES UNIT

Item	Symbol	Value
Line resistor (real(Zline))	R_{line}	0.1Ω
Line inductor(imag(Zline))	L_{line}	6.8 mH
Cut-off frequency of LPF	ω_f	0.7 rad/s
Nominal frequency	ω_0	314 rad/s
Frequency droop gain	K_P	0.002 rd/Ws
Voltage droop gain	K_Q	0.002 V/Var
Constant in SoC estimation	μ	$26000(\text{Ah}\cdot\text{V})^{-1}$
Load	Z_{load}	50Ω

$$\dot{X} = M_s X + C_s (I_s + E_s Y_s) K_s X = AX \quad (24)$$

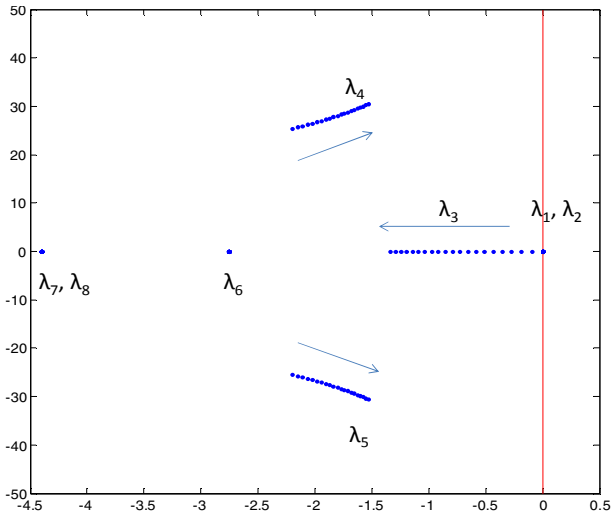
where $X = [\Delta\omega_1, \Delta\omega_{01}, \Delta e_{d1}, \Delta e_{q1}, \Delta\omega_2, \Delta\omega_{02}, \Delta e_{d2}, \Delta e_{q2}]^T$,

$$C_s = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix}, \quad M = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix},$$

$$K_s = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A = M_s + C_s (I_s + E_s Y_s) K_s.$$

The root locus plot of the system for K_{SoC} from 0 to 1 is shown in Fig. 5, with the control parameters shown in Table I. Two eigenvalues appear in the origin because the system matrix is singular due to the redundant state in the model, and thus not influence the dynamics. As can be seen, when K_{SoC} is

Fig. 5 Eigenvalue trace with different K_{SoC}

zero, λ_3 is redundant, and it is just like the conventional droop control, and when K_{SoC} increases, λ_4 and λ_5 move away from the real axis which will make the system more oscillating, so that K_{SoC} can be bounded.

IV. SoC INFORMATION DISCOVERY BASED ON DYNAMIC AVERAGE CONSENSUS

In order to get the value of SoC_{mean} , two alternatives are available. One possibility is to choose a supervisory node and make all the units communicate with this master and the average value is then passed down to each unit again after this supervisory node processes all the information it gets. However, this is method will cause heavy communication burden and it is prone to the failure of the supervisory node. Another alternative is to solve this problem in a distributed fashion through a family of algorithms known as average consensus, where each agent only exchanges information with a subset peers (e.g. their direct neighborhood in the communication network).

Here we model the multi-agent network as an undirected and connected graph with a set of agent N and a set of edges E , where each edge $\{i, j\} \in E$ represents a bidirectional communication link between two distinct agents. Each agent i stores a state with an initial value, which will be updated in each iteration with the iteration counter value k , and finally reach an agreement on the average of the state. Essentially, the consensus algorithm can be described in two steps: 1) each agent i communicate with its immediate neighbors to exchange the value of the state; 2) all the agents update their state information through a protocol which is a linear combination of their own state information and the state information of their neighbors obtained from last step.

In this application, the state of interest is the SoC of DES unit. The consensus approach used here is based on dynamic average consensus algorithm [14], which is the discrete time algorithm of [15]. The information discovery process for agent i is represented as follows.

$$SoC_{mean_i}(k+1) = SoC_{ini_i} + \sigma \sum_{j \in N_i} \delta_{ij}(k+1) \quad (25)$$

$$\delta_{ij}(k+1) = \delta_{ij}(k) + SoC_{mean_j}(k) - SoC_{mean_i}(k) \quad (26)$$

Where SoC_{mean_i} is the average SoC of DES calculated by agent i , SoC_{ini_i} is the initial SoC of DES unit i , and σ is a scaling factor, which is designed according to the stability; here σ is chosen as $1/3$. After a limited number of iterations, the average SoC of DES calculated by each agent can converge by only communicating with their closest neighbor. At that point, each agent can make simultaneously their own decision in the same way.

The control diagram of the proposed approach for each DES agent is shown in Fig. 6. As can be seen in the bottom of the control diagram, each converter is controlled by droop controller which is imposed outside the current loop and voltage loop, as discussed in (1) and (6). The detailed design of inter loop can be found in [16]. To make the SoC balanced, frequency given is modified according to SoC_{mean} , i.e., the average value of SoC, based the method proposed in section III

TABLE II. PARAMETER OF THE SYSTEM

Parameters	Symbol	Value	Units
Power stage			
Nominal voltage	E_0	230	V
Nominal frequency	ω_0^*	314	rad/s
Line 1 resistor	R_{line_1}	0.12	Ω
Line 1 inductor	L_{line_1}	5.4	mH
Line 2 resistor	R_{line_2}	0.1	Ω
Line 2 inductor	L_{line_2}	6.8	mH
Line 3 resistor	R_{line_3}	0.09	Ω
Line 3 inductor	L_{line_3}	7.8	H
LC filter inductor for each DES unit	L_f	1.8	mH
LC filter capacitor for each DES unit	C_f	27	μF
Control parameters			
Cut-off frequency of low pass filter for each DES unit	ω_f	0.7	rad/s
Proportional frequency droop for each DES unit	K_{Pi}	0.002	rad/Ws
Proportional amplitude droop for each DES unit	K_{Qi}	0.02	V/Var
Proportional coefficient of frequency scheduling for each DES unit	K_{SoC}	0.15	-
DES unit parameters			
Initial SoC for DES unit 1	SoC_{int_1}	80	%
Initial SoC for DES unit 2	SoC_{int_2}	70	%
Initial SoC for DES unit 3	SoC_{int_3}	60	%
Constant for SoC estimation	μ	26000	(Ah·V)-1

part C. The information discovery of SoC_{mean} is based on dynamic average consensus algorithm as just discussed. Each agent interacts with another only in terms of exchanging the updated SoC information.

V. HARDWARE-IN-THE-LOOP RESULTS

In order to verify the effectiveness of the proposed distributed control strategy, hardware in the loop simulation based on dSPACE is carried out. The tested system is a microgrid with three DES units connected in parallel to the common AC bus through transmission line, controlled by the MAS in a ring communication topology, as shown in Fig. 1.

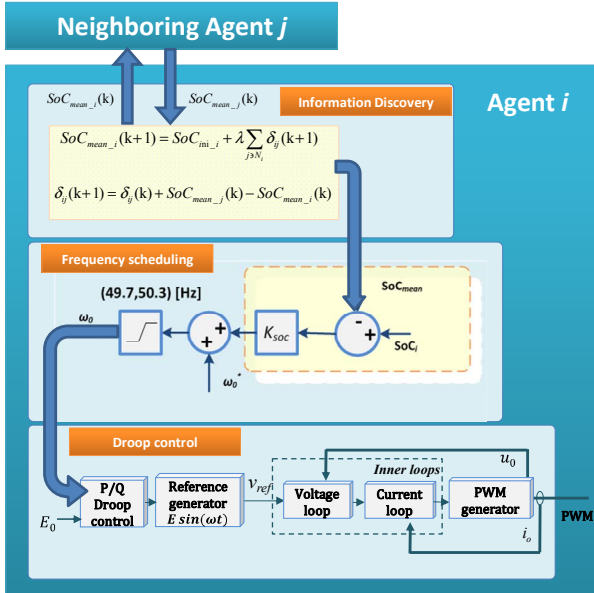


Fig.6 Control diagram for each agent

The power stage and control parameters are presented in Table II.

In order to test the effectiveness of the control system under different operation modes of the DES, the DES was at beginning supplying a load at 100 Ω in the discharging mode. At the time 20s, an extra 1700w real power was starting to be produced by RES in the microgrid, which will render the power to be surplus besides meeting the demand of the load and trigger the DES to change from discharging mode to charging mode. As can be seen in the Fig. 7, the values of SoC in different DES unit are converging in both the charging and discharging modes in (a) as the result of the real power is unevenly shared by each unit as shown in (b).

In order to test the robustness of the control system under certain communication topology changes, in addition to the power changes, in the meanwhile, communication link between unit 1 and unit 3 is disconnected at time 60.5s. As is shown in the Fig.7(c) and (d), the communication topology changes will cause a tiny disturbance of the consensus result of SoC_{mean} , and thus the trivial transient in the frequency given for the droop controller. However, this tiny disturbance brings no effects on the SoC of the DES unit and the real power it produces. According to average consensus theory, as long as the graph of the communication topology remains connected, consensus will be reached.

I. CONCLUSIONS

This paper proposed a distributed control method to achieve SoC balance for DES using frequency scheduling based on MAS. Instead of using adaptive droop gain, the possibility of modifying the frequency given is explored. A simple method based on the information of average SoC of the DES to adjust the frequency given is proposed. Frequency scheduling method is analyzed through small signal model to give the

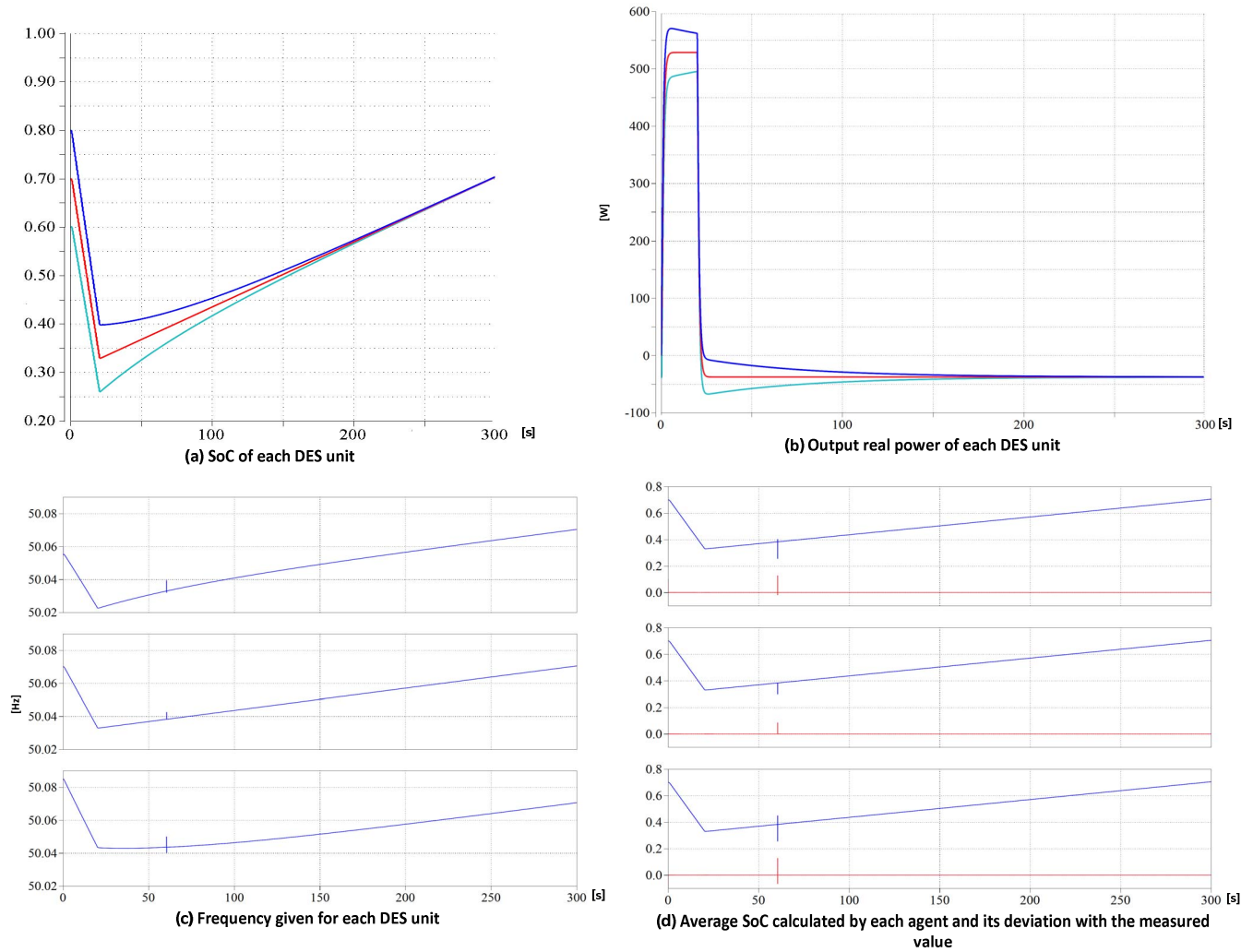


Fig. 7 Results of hardware in the Loop simulation

guide of choosing the control parameters of it. Average SoC of the DES is successfully discovered by dynamic consensus algorithm which offers robustness to the system against certain communication connection loss.

Promising directions for future work include testing the scalability, flexibility and “plug and play” features of this control strategy, considering power network topology and other objectives such as lifetime maximization, along with the implementation of this method to hybrid DES with distinctive charging/ discharging characteristics of different DES units.

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